High torque vane rheometer for concrete: principle and validation from rheological measurements

Patrice Estellé [*], Christophe Lanos

UEB, LGCGM EA3913, Equipe Matériaux et Thermo-Rhéologie, Insa/Université Rennes 1, 3 rue du Clos Courtel, BP 90422, 35704 Rennes Cedex 7, France

* Corresponding author

Email: patrice.estelle@univ-rennes1.fr
Tel: +33 (0) 2 23 23 42 00
Fax: +33 (0) 2 23 23 40 51

Abstract:

A high torque vane rheometer is used to measure the yields stress of cement-based materials. It is shown that this apparatus is suitable for the evaluation of the yield stress of various concretes and mortars in the fresh state in comparison with slump tests realized with ASTM Abrams cone. Then, the rheological properties (yield stress and shear flow behaviour) of a homogeneous kaolin clay suspension are studied with the apparatus and favourably compared with other rheometers and geometries.

Résumé:

Un rheomètre à haut couple équipé d'une géométrie vane est utilisé pour mesurer le seuil de mise en écoulement de matériaux cimentaires. Il est montré que cet appareil est approprié pour évaluer le seuil de mise en écoulement de différents bétons et mortiers à l'état frais en comparaison aux seuils déterminés au cône d'Abrams. Finalement, les propriétés rhéologiques (seuil d'écoulement et comportement sous cisaillement) d'une suspension d'argile de kaolin sont étudiées avec le rhéomètre à béton, et favorablement comparées à celles obtenues par d'autres rhéomètres et géométries.

Keywords:

Vane rheometer; fresh concrete; rheology, yield stress; slump

1. Introduction

Cement-based mixtures and concretes, as many suspensions, are yield stress materials including also thixotropic effects due to cement hydration. So a minimum stress has to be applied to the material for irreversible deformation and flow to occur. The yield stress of concrete is of great interest in practice for transportation, pumping and casting, and this rheological parameter plays a great role in formwork pressure development [1-3], sedimentation [4] and occurrence of distinct layer casting [5]. The yield stress of concrete is currently evaluated from practical tests [6-8], and from the slump test in particular. The slump test is a simple test which is used for a long time to evaluate the workability of concrete. The slump test consists of a mold of a given conical shape which is filled with the tested material. The mold is lifted and the material flows under gravity on a horizontal smooth metallic plate. The slump *S* is the difference between the height of the mold at the beginning of the test and that of material after flow stoppage. Several attempts have been made for determining the yield stress of concrete from the slump test [9-15]. Previous works have shown that concrete rheometers can also be used to evaluate the rheological properties of fresh concrete, and the yield stress in particular [16, 17]. The principle of these rheometers is to measure the torque acting on a rotating tool immersed in the material or in contact with the material. One can distinguish respectively, coaxial geometry [18-20], impeller tools [21, 22] and parallel plate geometry [23]. The main difficulty lies then in converting the torque-rotational speed data of the tool into a reliable relationship between shear stress and shear rate. This can be done following several approximations and assuming a priori knowledge of the rheological behaviour of the concrete, which is mainly considered as a Bingham fluid. So, the basic principle currently used is to measure the relationship between the torque and the rotational rate which are converted from linear regression in Bingham model parameters, eg. yield stress and plastic viscosity. This can result in discrepancy in the yield stress measurement of concretes, made with different rheometers [24]. Actually, these apparatus provide the same rheological classification of concretes but they do not give the same absolute values of yield stress. It was also shown that concretes can exhibit shear thickening behaviour for which a Bingham model is not consistent.

The objective of this work is to evaluate the yield stress of different concretes and mortars with a high torque vane rheometer, in order to show the relevance of this device as a concrete rheometer, in comparison with the slump test. The design of the high torque vane rheometer is inspired from the IBB and ICAR rheometers [22, 25, 26] and consists in the measurement of the stress response on a bladed tool rotating in the material. Such a geometry is well known as a vane tool. Vane tool is widely used in rheology [28-34] as reviewed in [35,36]. It is also used for measurements in cementitious materials, as done in [37-40] as example. This geometry has two major advantages: the fluid structure is less disturbed by the vane entry than for a larger tool, which is crucial for structured and granular suspensions like concrete, and wall slip is subsequently reduced [35,41]. The main differences between the device presented here and the ones used in previous studies [16, 17] are:

- The size of the gap between the vane and the outer cylinder wall. This gap is larger than several diameters of the largest coarse aggregate used in concretes. This is important to reduce the effect of change in particle packing near the wall,
- The size of the vane probe is larger than the one of the ICAR rheometer,
- The torque range which allows firm concretes to be tested,
- The method for computing the shear flow behaviour of the tested material.

The following section presents the materials investigated in this work. Section 3 shows the components and the working principle of the high torque vane rheometer, the derivation of vane shear flow data and the experiments. Finally, the main results are reported in section 4: we first show the efficiency of the high torque vane rheometer as a practical tool of concrete rheometry comparing the numerical prediction of the ASTM cone slump in term of concrete yield stress and density proposed in [14] with experimental slump flow values and measured yield stress obtained from high torque vane test for various fresh concretes and mortars. Then, we investigate the yield stress and the shear flow behaviour of a homogeneous suspension of clay in water with the fabricated rheometer, the results being compared with others rheometers and geometries.

2. Materials

2.1 Industrial concretes

The industrial concretes presently investigated are intended to be cast under vibration and are used to produce reinforced concrete slab and prestressed beams. The composition of concretes is confidential. It is not necessary here as the link between concrete mix design and its flow properties in the fresh state is beyond the scope of this paper. We focus here on the validation of the rheometer compared with other test geometries as slump test in particular. For all industrial concretes investigated, cement proportioning is close to 350 kg/m^3 of fresh concrete. The quantity of water is such that the solid volume fraction is close to 0.85, and superplasticizer admixture was used. Each batch of concrete is made on site with an industrial concrete-mixer of $1.25 m^3$. The concrete sample required to make the rheological measurements is taken before the moulding.

2.2 Mortars

The investigated mortar components were proportioned using Portland cement CPA CEM I 52.5 combined with limestone filler Betocarb P2. A siliceous dune sand (0/4 mm) was used. The sand has a specific gravity of 2.61. A polycarboxylate-based superplasticizer with a specific gravity of 1.07 and a solid content of 33% was employed. Commercial metal fibers

Dramix Sika were also used. The fibers have an aspect ratio of 55, where the aspect ratio is defined as l/d with l and d the length and diameter of the fibers respectively, with l=30mm. The composition of the different mortars is detailed in Tab.1. The mortars were prepared using a concrete-mixer at 20 rpm according to the following procedure. The dry sand is first mixed during 30s before introducing the fibers and 1/2 of mixing water. After 1min mixing, the cement and the filler are introduced into the concrete-mixer and mixed for 30s. Finally, the remaining water and the superplasticizer are added and the whole of the mixture is mixed for 1min.

2.3 Kaolin clay suspension

A kaolin clay suspension expected as a homogeneous simple yield stress fluid was prepared. Powdered Polwhite BB from Imerys (Kaolins de Bretagne, Ploemeur, France) was used to prepare clay suspension. Chemical and physical properties of clay are reported in Tab. 2. The water to clay weight ratio used here was 1. The measured density of the paste is close to 1400 kg/m^3. The suspension was prepared mixing the clay with water in a concrete mixer for 4 minutes at 20 rpm.

3. Experiments

In this section we first present the high torque vane rheometer, the principle of the yield stress measurement of concretes and mortars realized with this apparatus, and the procedure to compute the vane shear flow data. The principle of slump measurement made with the ASTM Abrams cone is also presented. Then, we detail the rheological measurements performed with the kaolin clay suspension. Rheological, slump and density measurements were realized five minutes later than the end of the mixing procedure of the materials. The mixing processes and experiments were conducted in a controlled ambient temperature of 20 ± 2℃.

3.1. High torque vane rheometer: principle and measurement methods

A schematic picture of the fabricated rheometer is shown in Fig.1 to describe its components and working principle. The vane rheometer consists of a motor ① which provides a maximal rotational velocity of 4000 rpm. This motor is fitted to a rotational velocity reducer ②, which finally provides a maximal rotational velocity of 120 rpm. A sensor ③, located between the transducer and the tool, is used to generate a controlled measure of both rotational velocity and torque during experiments. The torque measurement is frictionless. The torque value being able to be measured varies between 0 to 100 N.m. This corresponds to concretes having a yield stress varying between 0 and 17kPa if we consider the equation (1) and the dimension of the four-bladed tool presently used. The uncertainty in torque measurement is

0.1Nm. This induces an uncertainty in shear stress of 17Pa. The tool, see ④ in Fig.1, which is coaxially centered with the container before experiments, is immersed into the sample of material by moving up the container using a lifting table⑤. A PC interface communication ⑥ allows the instrument to be used imposing the rotational velocity of the probe from a specific software via a control device ⑦ and recording the measured torque as well as the real rotational velocity ⑧. The data acquisition rate is 10^{-1}s. The four-bladed tool used here is 156.5 mm in diameter D and 150 mm in height h. The internal diameter of the cylindrical container is 350 mm. This results in a gap size of 96.75mm, which is larger than several diameters of coarse aggregates generally used in concretes, and a radius ratio of 0.44.

The yield stress of materials is measured in two replicates with the high torque vane rheometer under rate-controlled mode [30], and the yield stress is defined by the shear stress plateau if the material is not thixotropic or by the maximum shear stress value if the material is thixotropic. In this way, tests are carried out at a constant and low rotational rate of 1 rpm for 1 min. This experimental procedure is similar to the stress growth test [22,32] or the vane method [29, 31]. The operating rotational rate is here reasonably low, as concretes, excluding self-compacting concretes, have a high yield stress. During experiments, the top of the vane was placed at the material surface. The surface of the cylindrical container is roughened to ensure no-slip at the wall during test. The roughness is close to 1 cm due to the large size of the coarse particles generally used with concretes. However, it should be noted that the material remains always partially sheared within the gap, due to the low rotational velocity of the tool presently used for the yield stress determination and the wide gap between the tool and the container.

The shear stress and shear rate are expressed following Couette analogy. It is thus assumed that the material is sheared along a cylindrical surface defined by the vane dimensions and that the stress distribution is uniform over the cylindrical sheared surface. So, the shear stress reduces to equation (1) if the end effects are neglected, as previously used in [28,33,36,38,42]. It is related to vane geometry and recorded torque M during test.

$$\tau = \frac{2M}{\pi h D^2} \qquad (1)$$

The shear rate is related to the vane geometry and set of torque velocity data (M ; Ω) from two equations depending on the flow condition within the gap between the vane tool and the cylinder [33]. The use of the maximization of the dissipation of energy allows discriminating between the partially sheared gap solution and the fully sheared one. So, from a series of increasing or decreasing rotational velocity Ω, the shear rate is computed as well as the corresponding shear stress.

This procedure allows in particular to avoid gap size approximation, shear factor calculation and the priori knowledge of the rheological behaviour of the material [33,43]. This method was previously developed in detail and its relevance was shown for Newtonian, non-Newtonian and yield stress fluids in [33,44-46].

3.2 Slump test

We presently used the ASTM Abrams cone technique [6] for slump measurement of materials. So, the height of the cone is 30 cm, the radii are respectively 20 cm for the base and 10 cm for the top. The cone is placed on a rigid metallic plate then filled with the material. The cone is lifted and the measured slump *S* is the difference between the height of the mold at the beginning of the test and that of material after flow stoppage. It was shown that this test allows to determine the yield stress of tested material, as reviewed and investigated by Roussel and Coussot [13]. Moreover, it was proposed in [14] a numerical relationship to predict the ASTM cone slump in term of concrete yield stress and density. It results from this work a simple approximation between the slump *S*, the yield stress τ_0 and the density ρ of the concrete which expresses as follows.

$$S = 25.5 - 17.6\frac{\tau_0}{\rho} \qquad (2)$$

This approximation was also checked by [14] comparing equation (2) with experimental slump and yield stress values of concretes. In the same way, it is the purpose in the following to compare the numerical prediction of Eq. (2) with the measured slump of various fresh concretes and mortars as well as their yield stresses obtained independently from high torque vane measurement.

3.3 Measurements with the kaolin clay suspension

The yield stress of the kaolin clay suspension was evaluated with the high torque vane rheometer as proposed above, as well as its slump. For comparison purpose, the yield stress of the kaolin clay suspension was also evaluated from a Brookfield Soft Solid Tester equipped with a four-bladed vane tool of 16 mm in both diameter and height immersed in a large baker with roughened surface. A rotational rate of 1 rpm for 1 min was also applied. These three measurements were made after a five minute resting time of the kaolin suspension.

In addition, the shear flow behaviour of the kaolin clay suspension was investigated with the high torque vane rheometer. After a high preshear, a linear down ramp in controlled velocity of 45 to 0 rpm in 2mins was applied to the clay suspension without resting time of the clay suspension before the ramp. This was realized in two replicates and no difference was achieved. The vane shear flow data were computed from the procedure described in section 3.1.

Moreover, the shear flow behaviour of kaolin clay suspension was determined independently and simultaneously using a Malvern Gemini rheometer equipped with a parallel-plate geometry of 40mm in diameter and 2mm in gap. Sand paper was glued on both plates to prevent slippage. The clay suspension was also preshear at high shear rate before applying a rate-controlled measurement in the shear rate range 100-0s^{-1} in 100s, from the rheometer software. The linear down ramp was applied to the clay suspension without resting time before the ramp. Two replicates of these tests were also performed and provide the same shear flow curve as the one described in Fig.4.

4. Results and discussion

The tested concretes and mortars exhibited the typical curves shown in Fig.2. The low overshoot presented by the shear stress in a shear stress vs time plot of figure 2 indicates that the investigated concretes behave as low thixotropic materials. A similar trend was obtained for all the concretes and mortars tested. As mentioned in [27,29,31], the curves evolve in three stages. First the stress increases quite linearly up to a break from linearity which is defined as the yield point. Then the stress reaches a maximum value, then decreases and tends to a constant value. The first part of the curve represents the elastic response of the material until the peak which corresponds to the yield stress value of the material. Then, the material flows and the last part is associated with the structure breakdown of the material under shear.. Fig.2 also shows low shear stress fluctuations beyond the yield point which can be explained by the movement of the coarse particles of the concretes and the sensitiveness of the torque transducer.

As mentioned above, we focus here on the yield stress value of the concretes. So, Fig.3 compares the numerical prediction of Eq. (2) with the measured slumps and the yield stress values obtained from the vane measurements. Fig.3 shows that a quite good agreement is achieved between the numerical prediction and the measurements. So, the high torque vane rheometer provides a reliable evaluation of the yield stress of concretes and mortars investigated here, in the tested range of yield stress values. While it is not the purpose here to compare the yield stress of fluids in function of material composition, we can mention that the yield stresses of industrial concretes are larger than the one of mortars, probably due to the presence of coarse particles.

The yield stress of the clay suspension is evaluated respectively to 458 Pa with the high torque vane rheometer, and to 438 Pa with the Brookfield soft solid tester. So, the relative deviation is 4.6%. This is of the same order of magnitude as the experimental error. The measured slump of the clay suspension S is 19 cm. We can see in Fig.3, the agreement between the numerical prediction of Eq. (2) and the measured slump and yield stress of the kaolin clay suspension. This is similar to the results obtained by [13] considering a cement paste as a homogeneous yield stress fluid and using ASTM minicone.

Fig.4 compares the apparent viscosity of the presheared kaolin clay suspension between parallel plate measurement and high torque vane data. The shear rate range induced by the vane measurement varies between 10^{-3} and 10 s^{-1}, which is similar to the shear rate range obtained by Heirman et al [18] with the last version of the BML viscometer. As can be seen, the parallel plate and high torque vane data compare well within the shear rate range of 0.5 to $10s^{-1}$. This allows to conclude about the efficiency of the high torque vane rheometer in shear flow measurement. Finally, it is shown that the clay suspension investigated seems to behave as a simple shear thinning material. There has been some change in clay suspension structure during the high preshear. As no resting time was applied before the descending ramp, and the time of this ramp is very short, the suspension does not retrieve its initial structure. However, at the flow stoppage, the yield stress value tends to 296 $\pm$ 2 Pa. This is different and lower than the yield stress at which the flow starts which is obtained from the vane method.

5. Conclusion

In this paper, a high torque vane rheometer was used to evaluate the yield stress of various concretes and mortars. It was concluded that this rheometer is able to correctly evaluate the yield stress of these materials in comparison with slump test. Results are in agreement with the numerical prediction between slump and yield stress of concretes, as previously shown in the literature. The high torque vane rheometer was also tested with a homogeneous kaolin clay suspension. It was shown that the yield stress and the shear flow behavior of this suspension are correctly predicted by the vane rheometer, the results being compared to those obtained from other rheometers and geometries. Once validated, the concrete rheometer with the vane geometry has to be used now to investigate the rheological properties of concretes in the fresh state in relation with their composition. This is the objective of future works.

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Figure Captions

Figure 1. Schematic diagram of the experimental setup (left) – View of the high torque vane rheometer (right).

Figure 2. Typical curves of concretes with vane test in rate-controlled mode. Upper curve: example of concrete produced for reinforced slab - lower curve: example of concrete produced for prestressed beams.

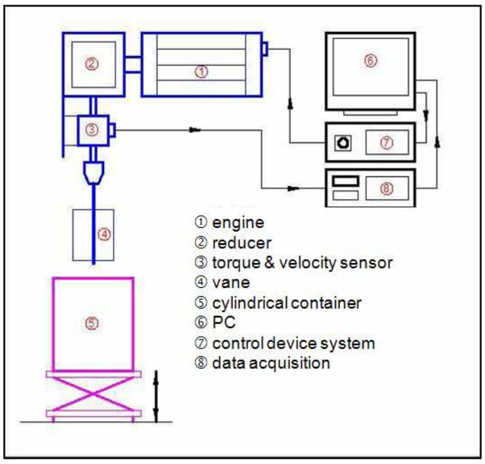
Figure 3. Yield stress-slump correlation – Comparison between numerical prediction and experimental results.

Figure 4. Apparent viscosity of kaolin clay suspension versus shear rate – comparison between the high torque vane rheometer and the parallel plate geometry.

Table Caption

Table 1. Mortar components

Table 2. Chemical and physical properties of clay



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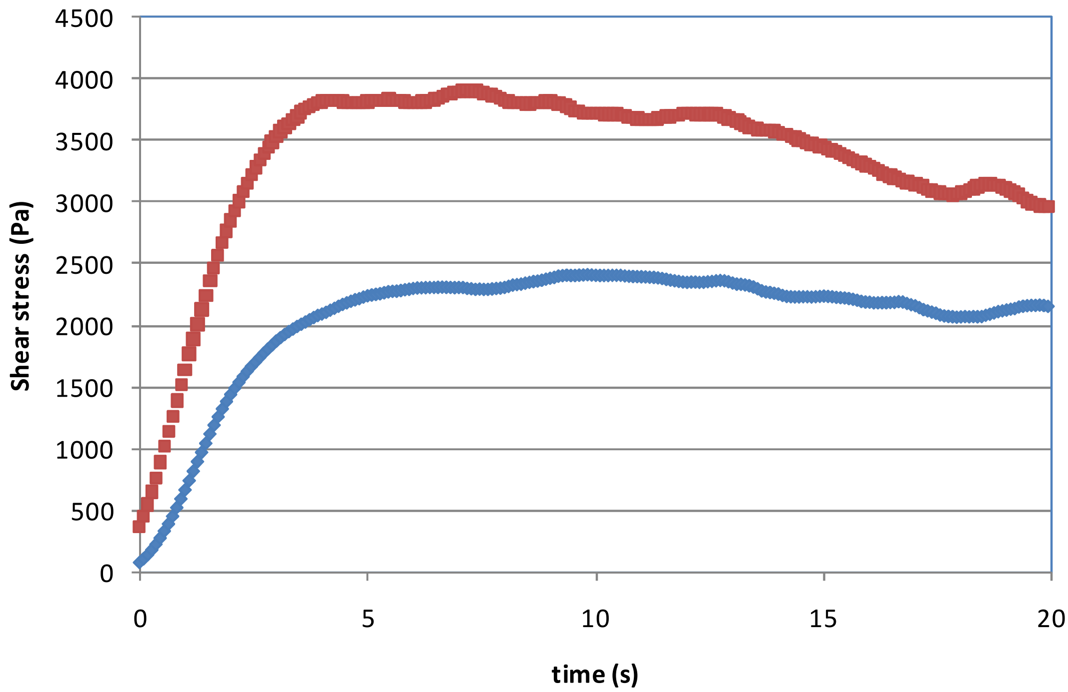

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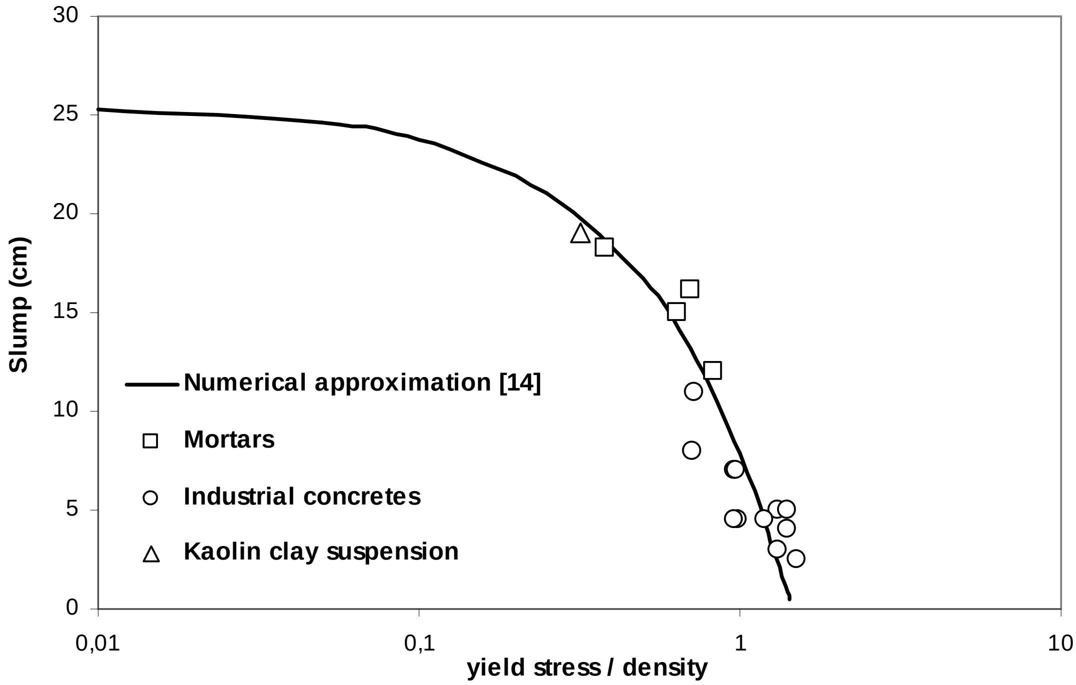

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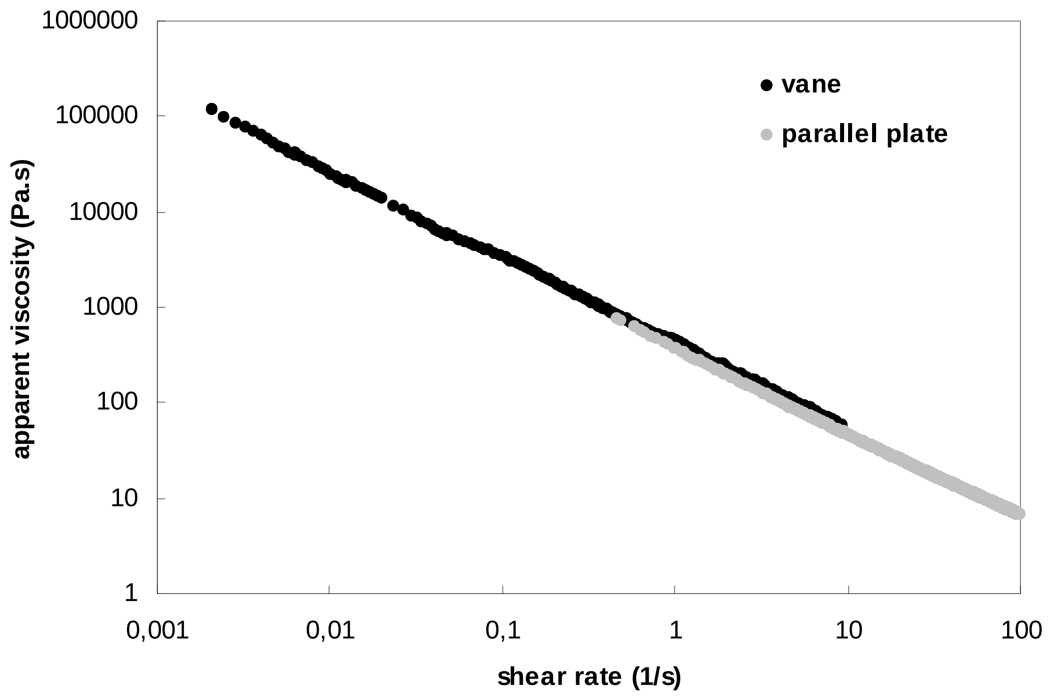

Figure 4. Apparent viscosity of kaolin clay suspension versus shear rate – comparison between the high torque vane rheometer and the parallel plate geometry.

Table 1. Mortar components.

Mortar	1	2	3	4
Sand 0/4 (kg/m^3)	1427	1042	1074	1356
Cement (kg/m^3)	350	450	450	450
Filler (kg/m^3)	200	100	335	64,7
Water (kg/m^3)	220	225	270	270
Superplasticizer (%)	0,78	0	0	0,64
Volume of fiber (%)	0	0,5	1,05	1,05
W/C	0,63	0,5	0,6	0,6
Density (kg/m3)	2096	2077	2186	2160

Table 2. Chemical and physical properties of clay

Specific gravity	2.6
pH	4.5
Surface area (BET; m^2/g)	10
Aerated powder density (kg/m^3)	390
Tapped powder density (kg/m^3)	750
SiO_2 (mass %)	48
Al_2O_3 (mass %)	37